# Top Mass at the Tevatron


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On behalf of the D0 and CDF Collaborations


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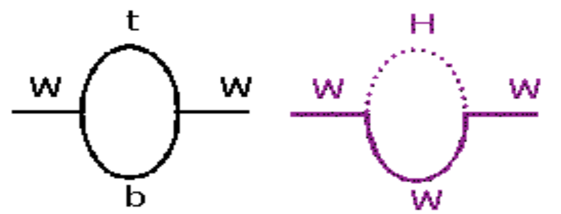
# Why do we care about Top Mass?

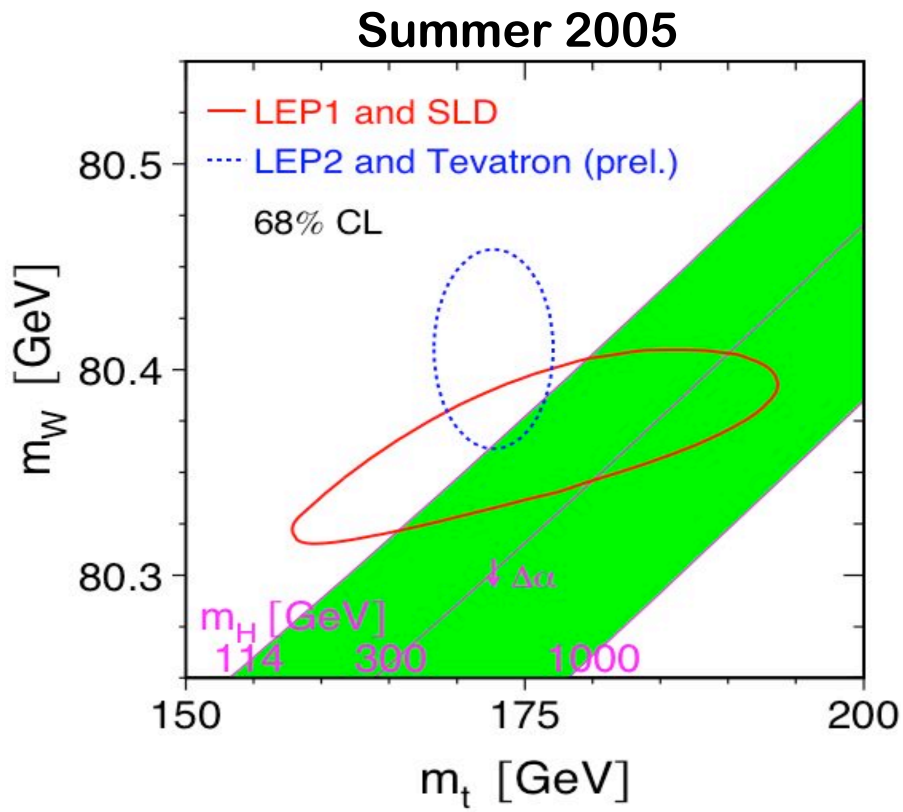
- Top mass is a fundamental SM parameter

  - important in radiative corrections:




$\Delta M_W \propto M_T^2$ $\Delta M_W \propto \ln M_H$

  - Yukawa coupling ~1

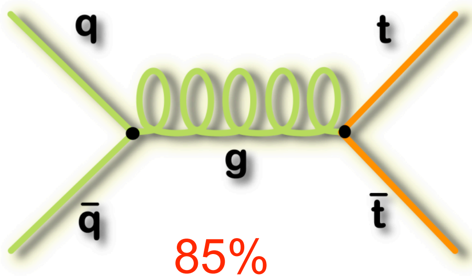



  - Consistency check of SM, and it constrains $M_{Higgs}$ with $M_w$ and other electroweak precision measurements

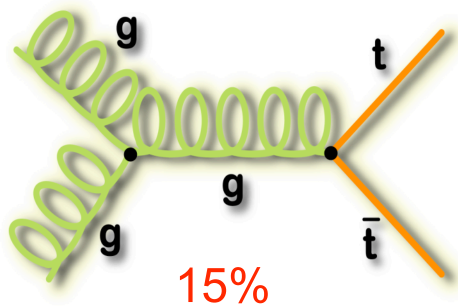
- A key to understand electroweak symmetry breaking?
- Constraint on SUSY models

# Top Production and Decay

- At the Tevatron, mainly primarily produced in pairs ($\sigma$~7pb) via strong interaction.




85%

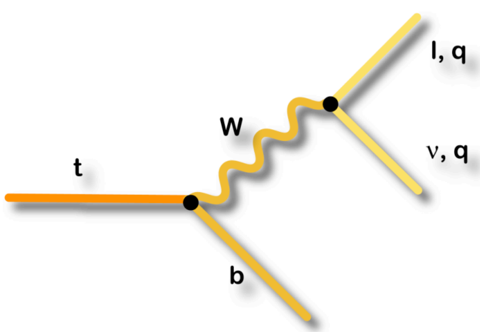



15%

LHC (90%)

~100$\sigma$

- Top decays as free quark due to large mass ($\tau_{top}$ ~ 4 x 10 $^{-25}$ s )




- Dilepton (5%, small bkgds)

  2 leptons(e/$\mu$), 2 b jets, missing $E_T$ (2$\nu$s)

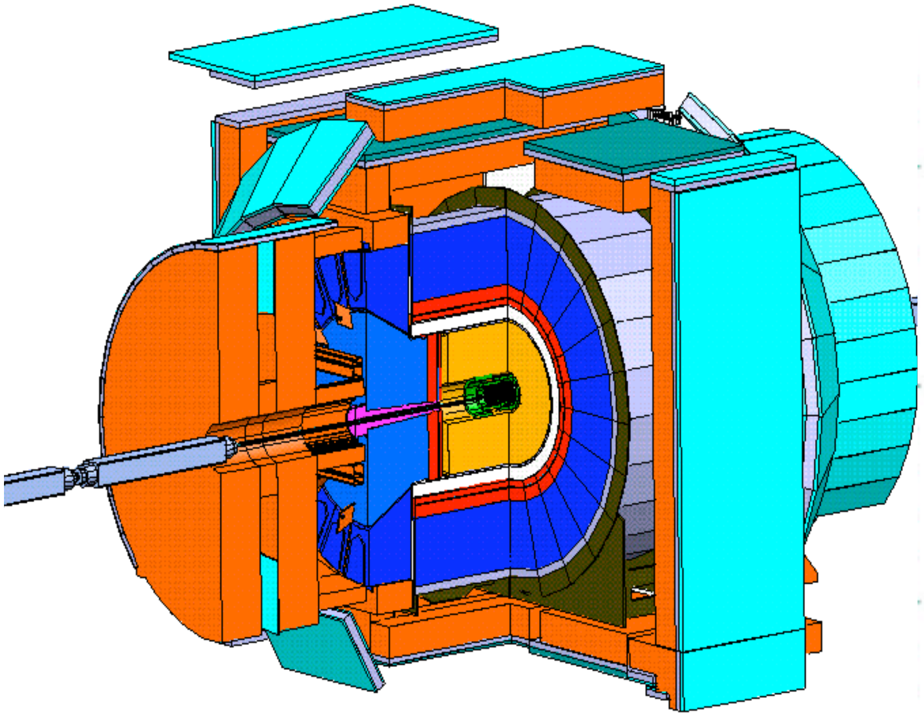
- Lepton+Jet (30%, manageable bkgds)

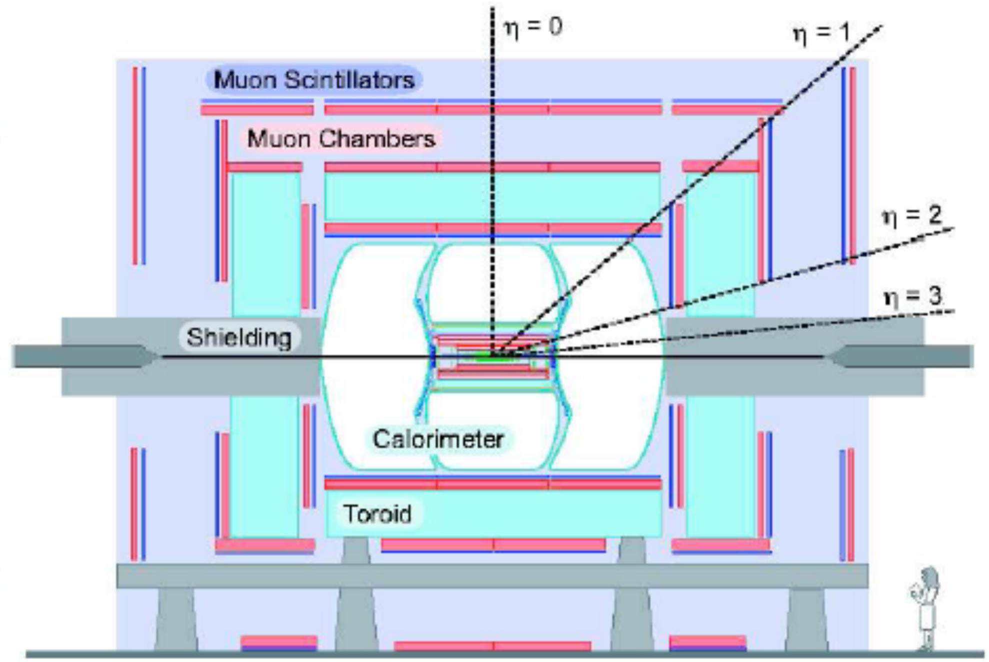
  1 lepton(e/$\mu$), 4 jets (2 b jets), missing $E_T$ (1$\nu$)

- All-hadronic (44%, large bkgds)

  6 jets (2 b jets)

# The CDF and DØ Detectors



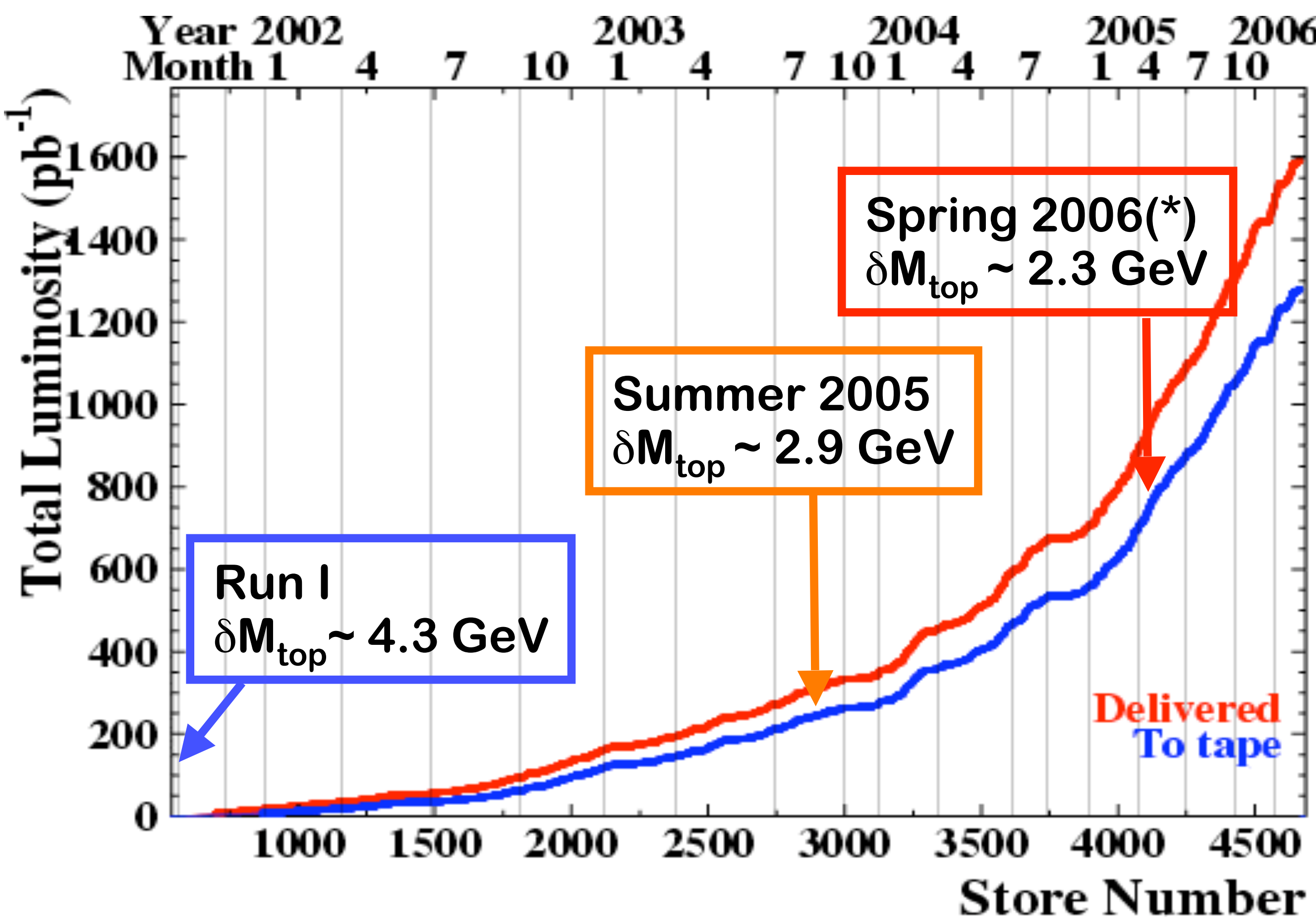



- Calorimeters (σ/E~ 80% /√E)
- Precision tracking with SI:
- Muon chambers
- Excellent muon coverage(D0), excellent tracking (CDF)

→

Multi-purpose detector;
precision measurements
search for new physics

# Great Performance
## (Tevatron, D0, and CDF)

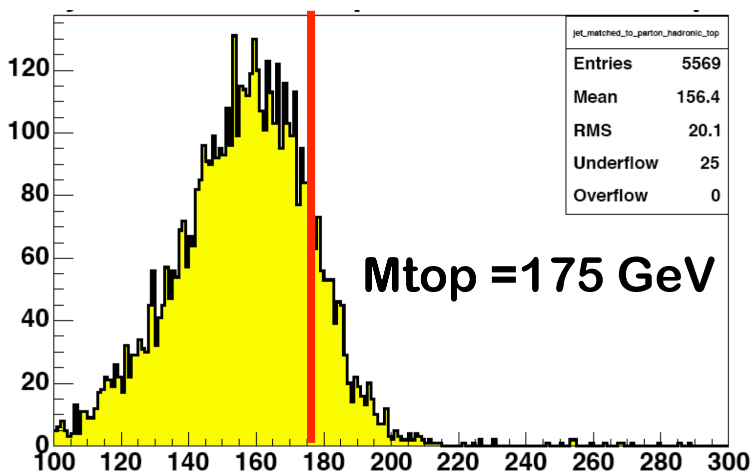



Recorded ~1.3 fb$^{-1}$
Peak Inst. Lum
~1.7E32 cm$^{-2}$s$^{-1}$

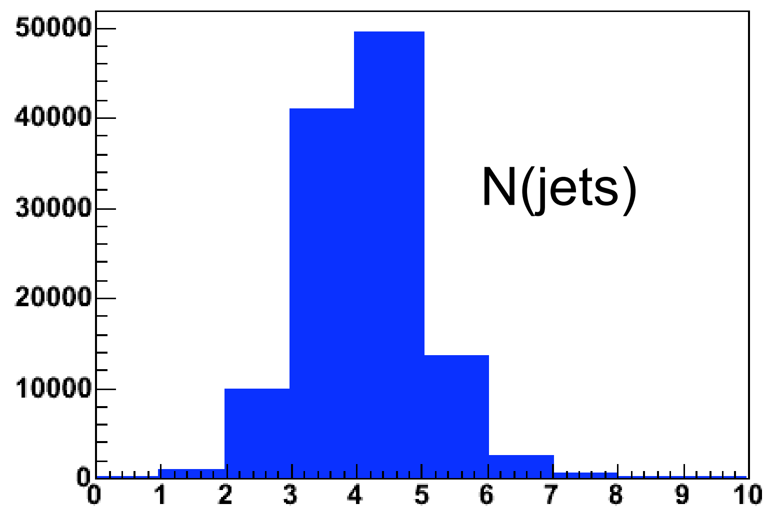
* Not all D0 data included

# $M_{top}$ Measurement : Challenge 1

- Not a just calculation of the invariant mass of W(jj) and b!!!




Why M(bjj) ≠ 175 GeV?




- Measured jet energy

  ≠ quark energy from top decay

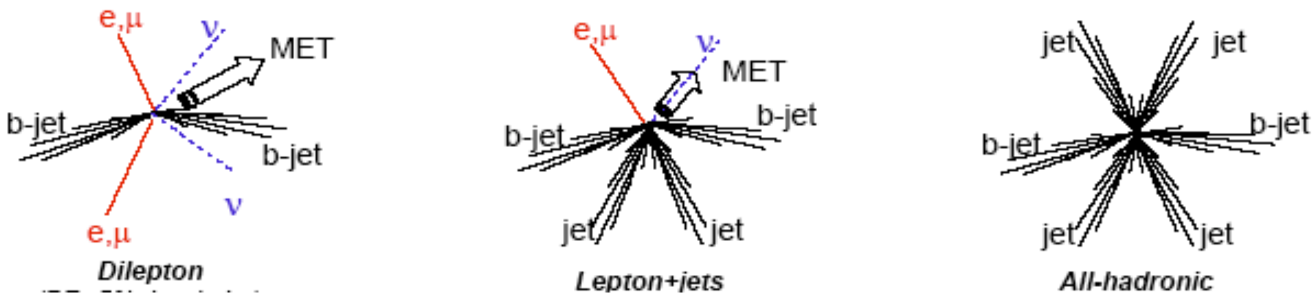
  - Quarks: showering, hadronization, jet clustering
  - Extra radiated jets

- Excellent jet energy correction and good modeling of extra gluon radiations (40%)

# Challenge 2

- There are two top quarks, not all final states available
  - Good to have more than one:but too many possibilities to find a correct combination (all jets: 90), not enough information for dilepton channel

3 constraints: two M(w)=80.4, one M(t)=M(tb)

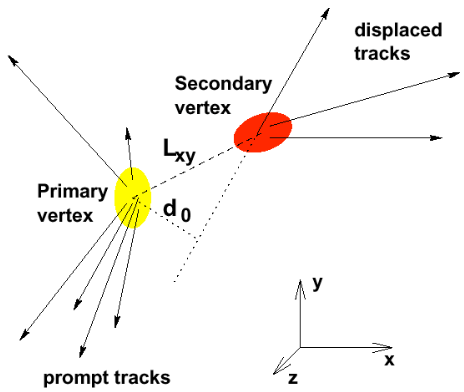


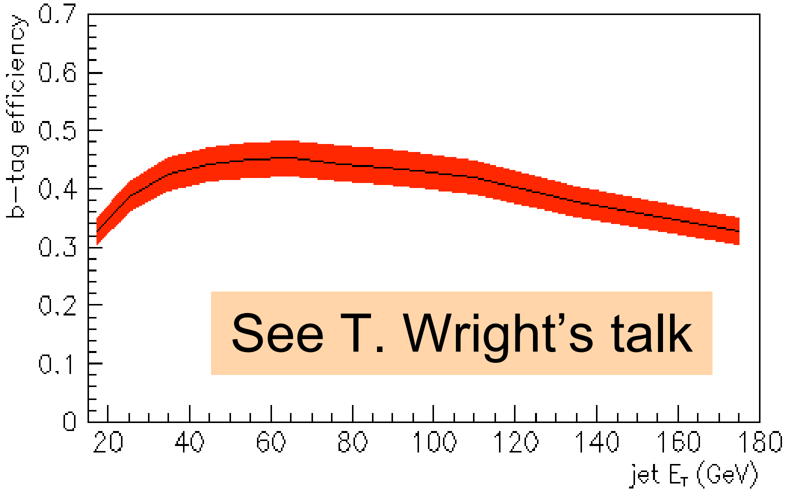

| Ncomb(btag) | 2(2) | 12 (6) | 360(90) |
|---|---|---|---|
| | 2 missing ν<br>Unconstrained:<br>Small BR | 1 missing ν<br>Overconstrained:<br>Golden Channel | No missing<br>Overconstrained:<br>Large bkgds |

- B-tagging help!

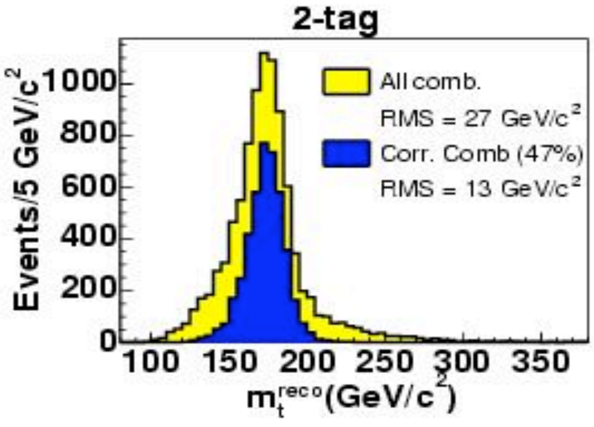
# B-tagging

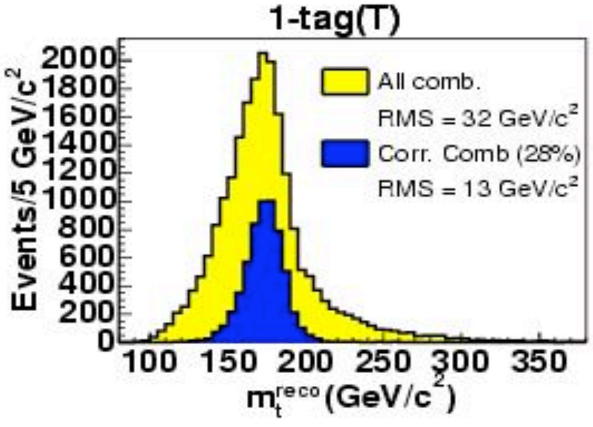
- B-tag: SecVtx tagger




- B-tagging helps: reduced wrong comb., and improves resolution.



# Top Mass Measurements

## Template

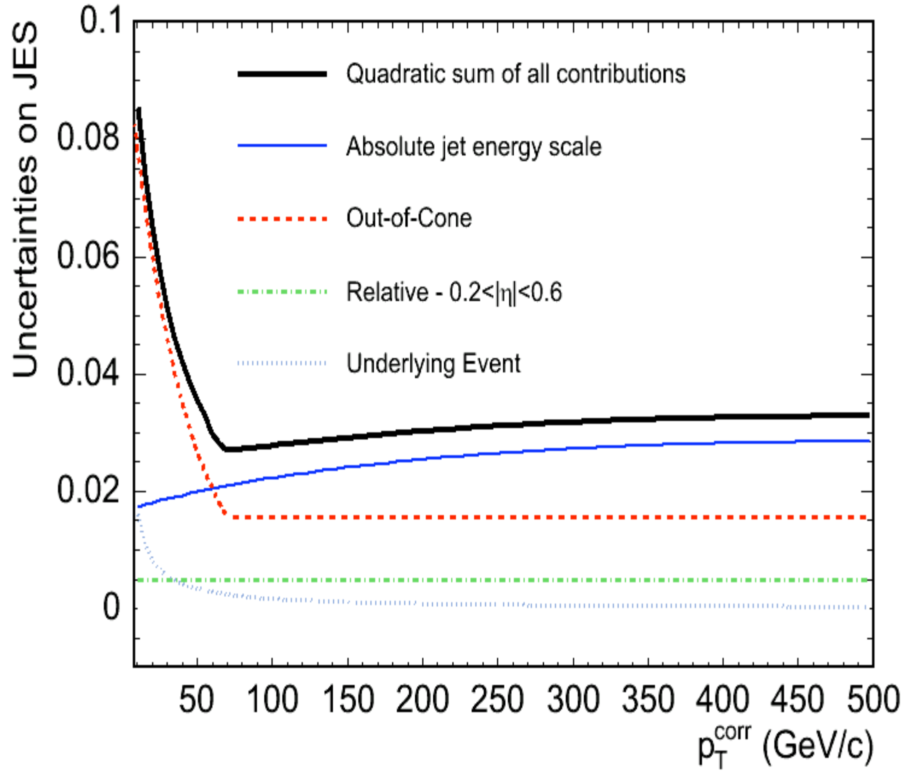
- Reconstruct $m_t$ event-by-event - the best value per each event
- Create "templates" using simulated events with different top mass values, and backgrounds.
- Maximum Likelihood fit using signal+backgrounds templates

## Matrix Element

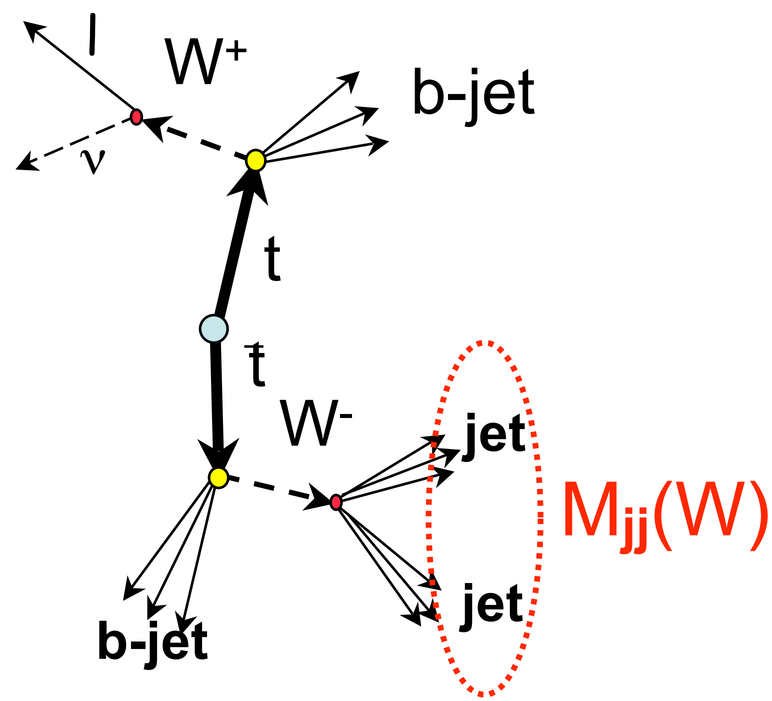
- Calculate probability as top massfor all combinations in each event by Matrix Element calculation
  - maximize dynamic info.
- Build likelihood directly from the probabilities.
- Calibrate measured mass and error using simulated events

# Jet Energy Scale(JES) Uncertainties

Standard Calib. (dijet, γ-jets etc)




In-situ Calibration




About 3% of $M_{top}$

See R. Hirosky's talk

JES uncertainty:
mostly statistical,
scaled with lum

Un-ki Yang, HCP 2006

# Strategy

- Precision
- Consistency (different channels, methods)
- New Physics (bias)

| | Method | Njets | | B-tag | | JES | | | Rec. variables |
|---|---|---|---|---|---|---|---|---|---|
| | | Exact | +extra | Yes | No | Wjj+std | Wjj | No | |
| LJ | TMP | 4 | | | | | | | mt, mjj, Lxy |
| | ME | | | | | | | | P(Mt,JES) |
| DIL | TMP | 2 | | | | | | | mt |
| | ME | | | | | | | | P(Mt) |
| All-J | TMP+ME | 6 | | | | | | | mt, mtb |

both

Only D0

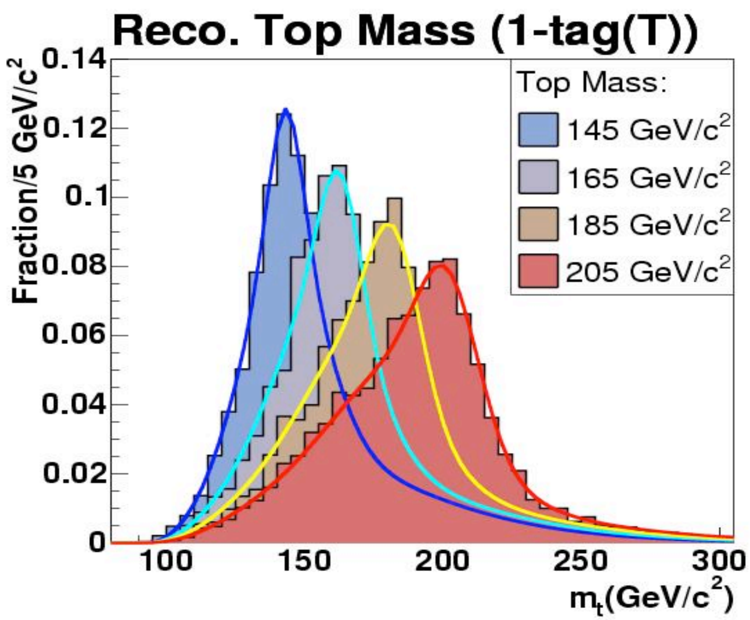
Only CDF

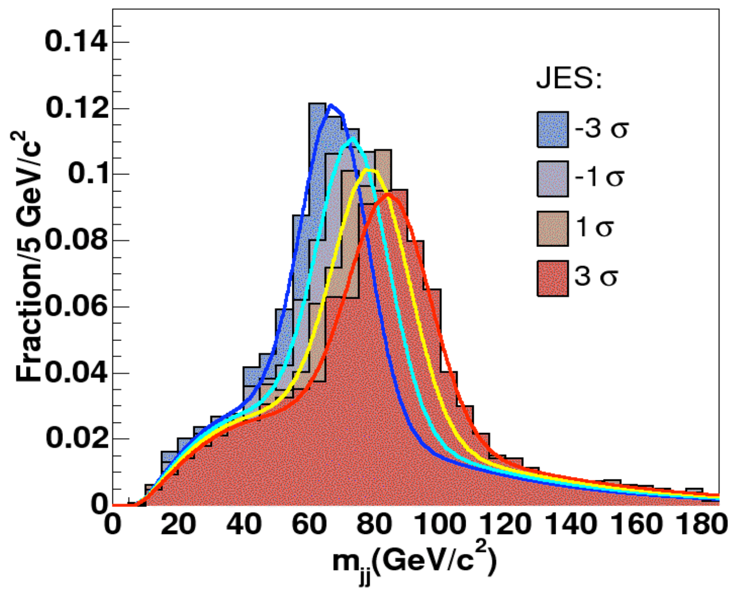
# Template Method in lepton+jet

- $\chi^2$ kinematic fitter

$$\chi^2 = \sum_{i=l,4\ jets} \frac{(\hat{p}_T^i - p_T^i)^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(\hat{p}_T^{UE} - p_T^{UE})^2}{\sigma_j^2}$$
$$+ \frac{(m_{jj} - m_W)^2}{\Gamma_W^2} + \frac{(m_{l\nu} - m_W)^2}{\Gamma_W^2} + \frac{(m_{bjj} - m_t)^2}{\Gamma_t^2} + \frac{(m_{bl\nu} - m_t)^2}{\Gamma_t^2}$$

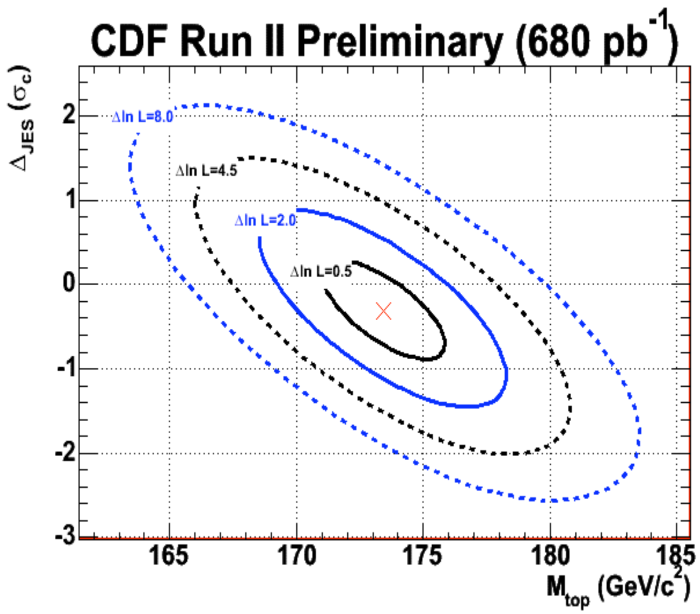
- Select reco. $m_t$ from assignment yielding lowest $\chi^2$




Mtop and JES : by likelihood fit using shape comparisons of $m_t$ & $m_{jj}$ dist.

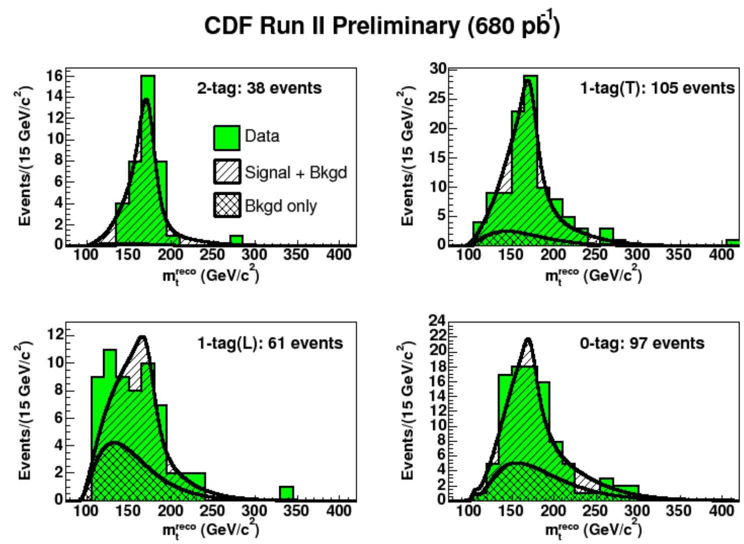
# Template Results in lepton+jets

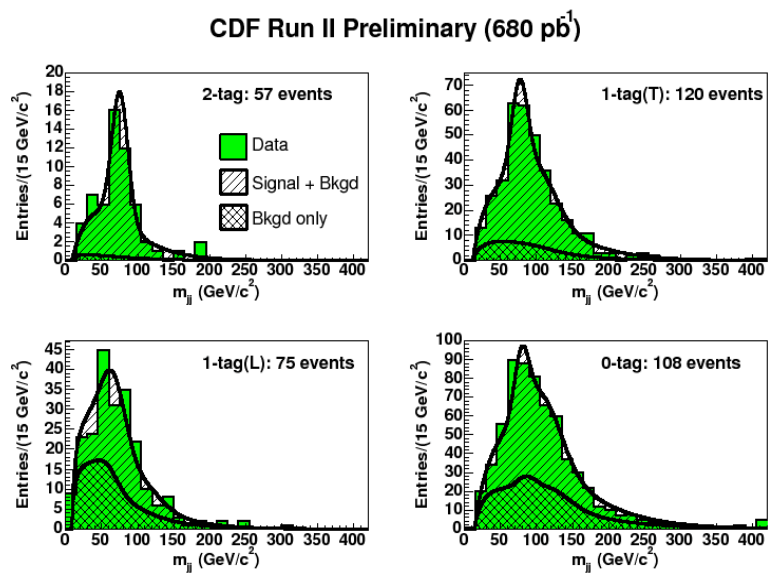



$$M_{top} = 173.4 \pm 2.5(\mathrm{stat.} + \mathrm{JES})$$
$$\pm 1.3\ (\mathrm{syst.})\ \mathrm{GeV}/c^2$$

**World best single measurement!**

40% improvement on JES
using in-situ JES calibration



# Matrix Element Method in lepton+jets

- Maximize kinematic and dynamic information
- Calculate a probability per event to be signal or background as a function of the top mass
- Signal probability for a set of measured jets and lepton (x)

$$P(x;M_{top},JES) = \frac{1}{\sigma}\int dq_1 dq_2 f(q_1) f(q_2) \quad d\sigma(y;M_{top}) \quad W(x,y,JES)$$

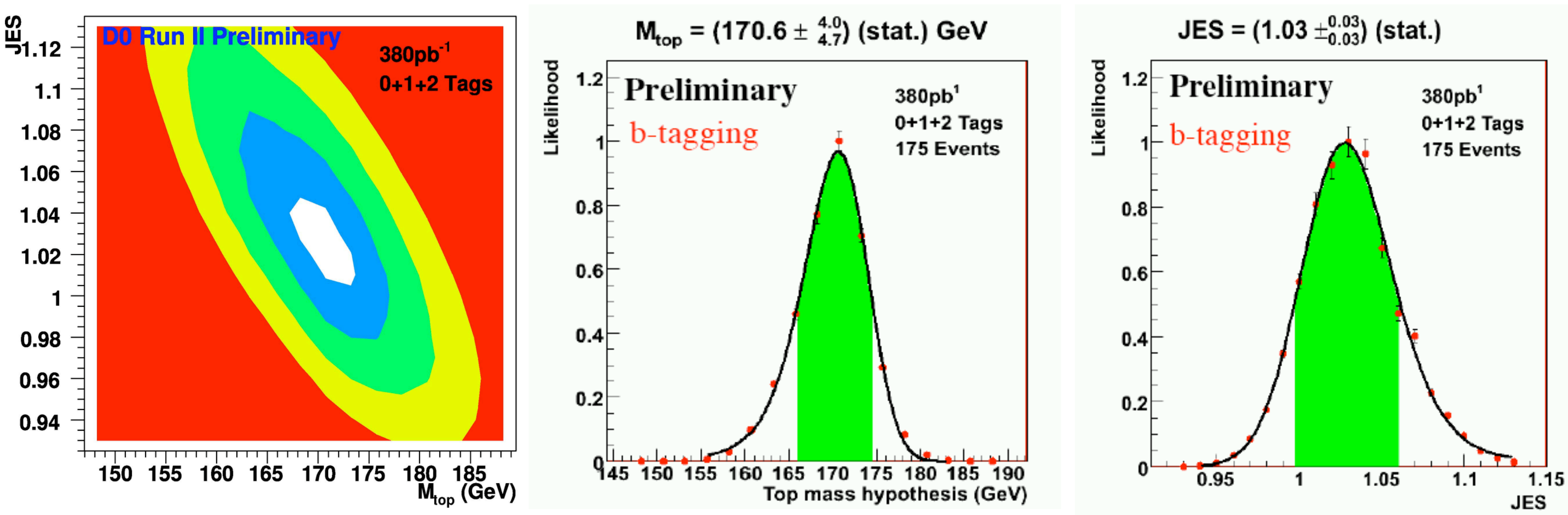
**Differential cross section: LO ME (qq->tt) only**

**Transfer function: probability to measure x when parton-level y was produced**

- JES is a free parameter, constrained in situ by mass of the W
- Background probability is similar, but no dependence on $M_{top}$

$$L(f_{top}, M_{top}, JES) \propto \prod_{i}^{Nevents} \left( f_{top}\, P_{top,i}(M_{top}, JES) + (1 - f_{top})\, P_{bkgd,i}(JES) \right)$$

# M.E. Results in lepton+jets



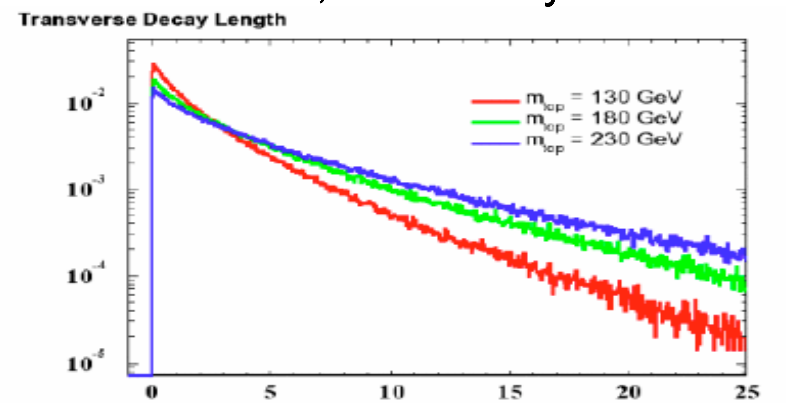

$$M_{top} = 170.6^{+4.0}_{-4.7}(\text{stat.} + \text{JES}) \pm 1.4\,(\text{syst.})\ \text{GeV}/c^2$$

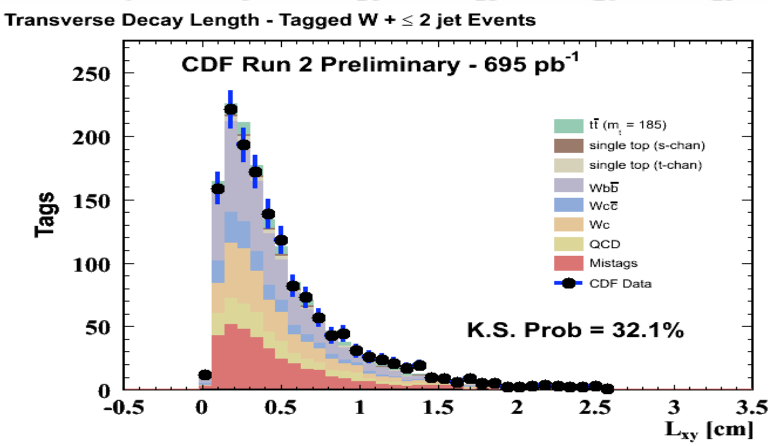
- Reduced the JES error with in-situ calibration, consistent with external calibration (JES=1)
- The b-tagging information improves δMtop(stat) by 35% (17% expected)

# Template using Decay Length (Lxy)

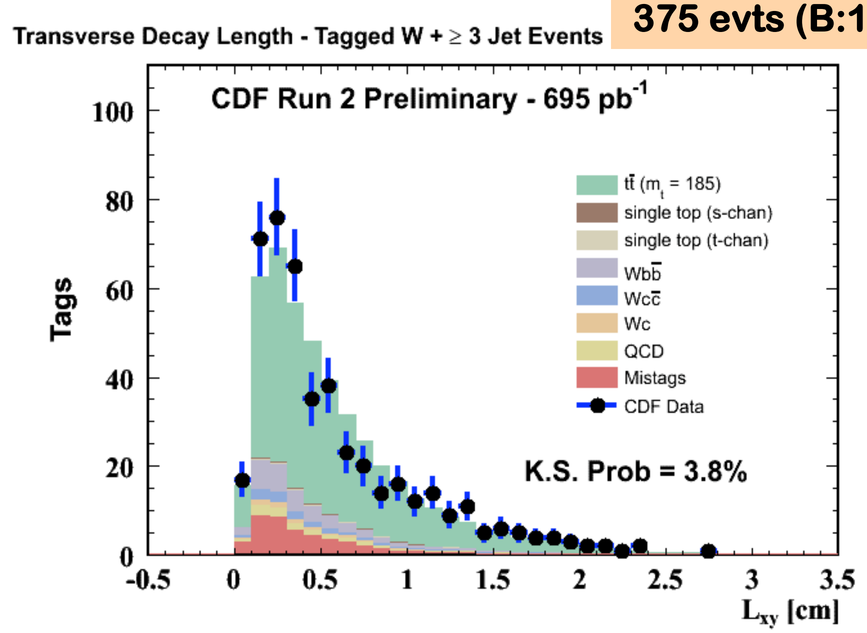
- Uses the average transverse decay length, Lxy of the b-hadrons
- B hadron decay length ∝ b-jet boost ∝ $M_{top}$ (>=3jets)

PRD 71, 054029 by C. Hill *et al.*




375 evts (B:111)

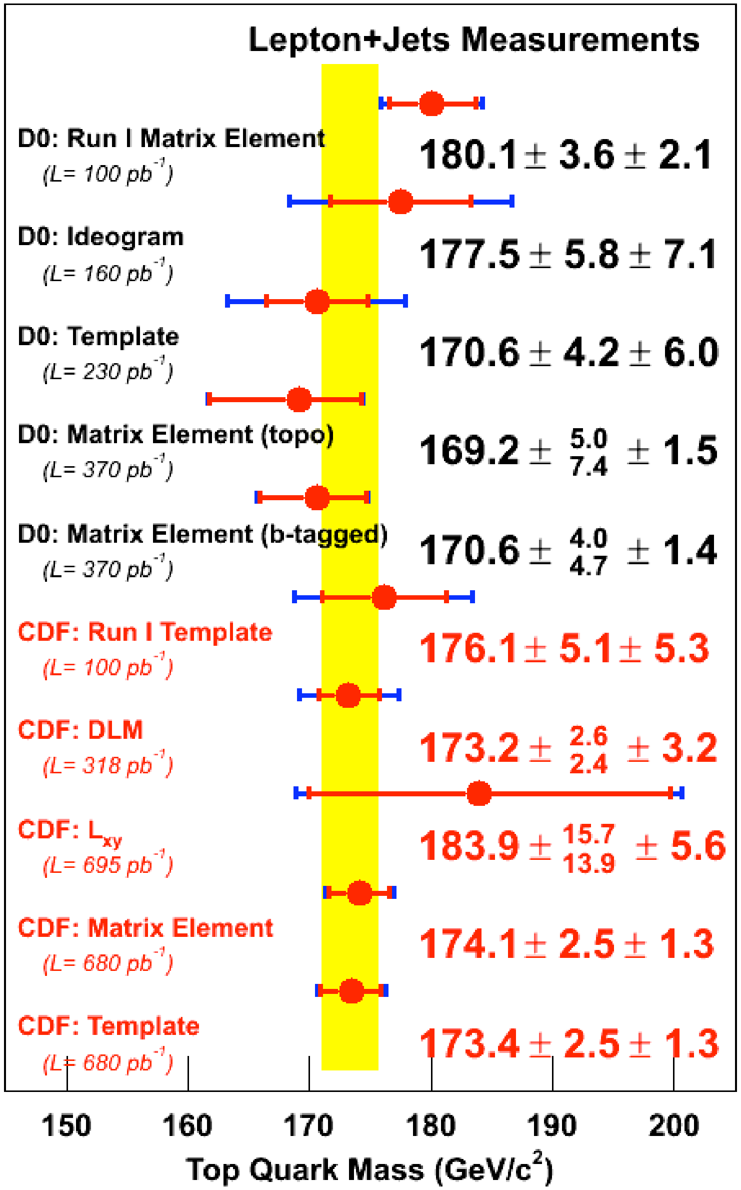



$$M_{top} = 183.9^{+15.7}_{-13.9}\,(\mathrm{stat}) \pm 0.3\,(JES) \pm 5.6\,(\mathrm{syst})\ \mathrm{GeV}/c^2$$

**Insensitive to JES, but need Lxy simulation**

Statistics limited, but can make big contributions at Run IIb, LHC

# Summary in lepton+jets

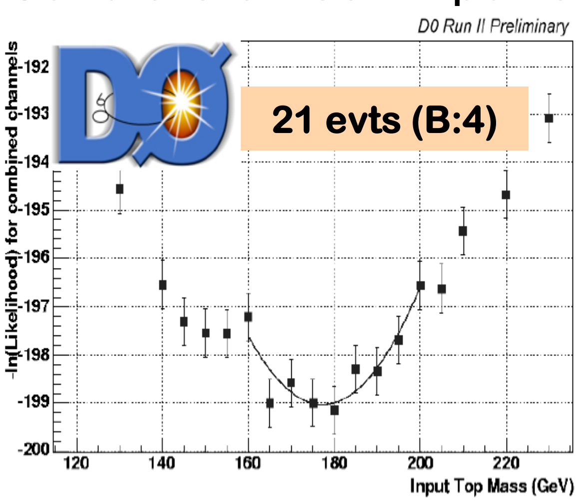


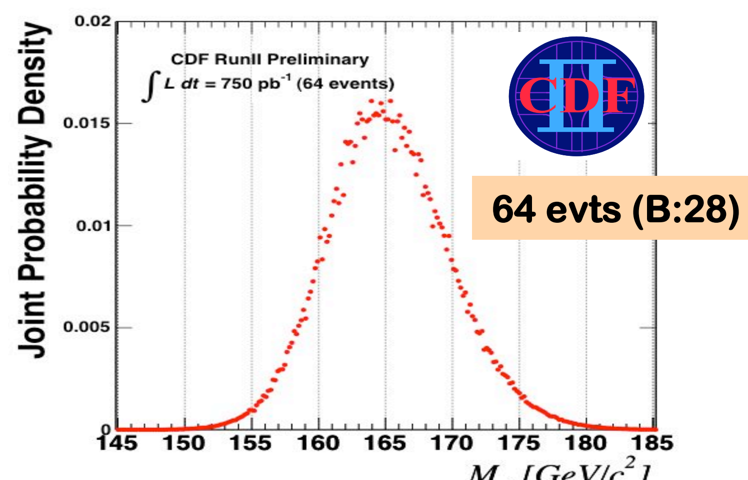

| Systematic $\Delta M_{top}$(GeV/c$^2$) | TMT (CDF) | ME (D0) |
|---|---|---|
| JES | (1.8) | (3.4) |
| Residual JES | 0.7 | 0.8 |
| B-jet JES | 0.6 | 0.7 |
| ISR/FSR | 0.5 | 0.5 |
| Bkgd Shape | 0.5 | 0.3 |
| Generators | 0.3 | |
| PDFs | 0.3 | 0.1 |
| Method | 0.3 | 0.5 |
| B-tagging | 0.1 | 0.2 |
| TOTAL | 1.3 | 1.4 |

All consistent!!

# Methods in dilepton

- Unconstrained system: 2 neutrinos, but 1 missing $E_T$ observable
  - Template:
    - Assume $\eta(\nu)$ (or $\phi(\nu)$, $P_Z(tt)$)
    - Sum over all kinematic solutions, and (l,b) pairs, select the most probable value as a reco. $m_t$
  - Matrix Element:
    - Integrated over unknown variables using the LO M.E., assuming jet angles, lepton are perfect, and jets are b's
    - Obtain P(Mtop) for signal and backgrounds
    - Calibrate off-set in pull and pull width using fully simulated MC

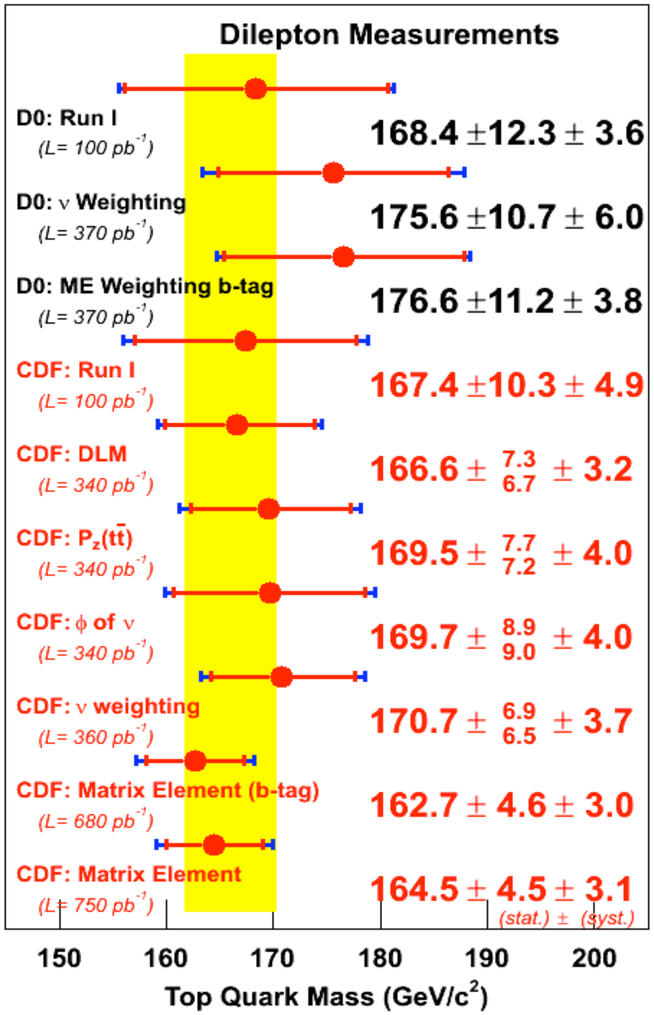



$$M_{top} = 175.6 \pm 10.6\,(stat) \pm 6.0(\text{syst})\ \text{GeV}/c^2$$

$$M_{top} = 164.5 \pm 4.5\ (\text{stat}) \pm 3.1(\text{syst})\ \text{GeV}/c^2$$

# Summary in dileptons

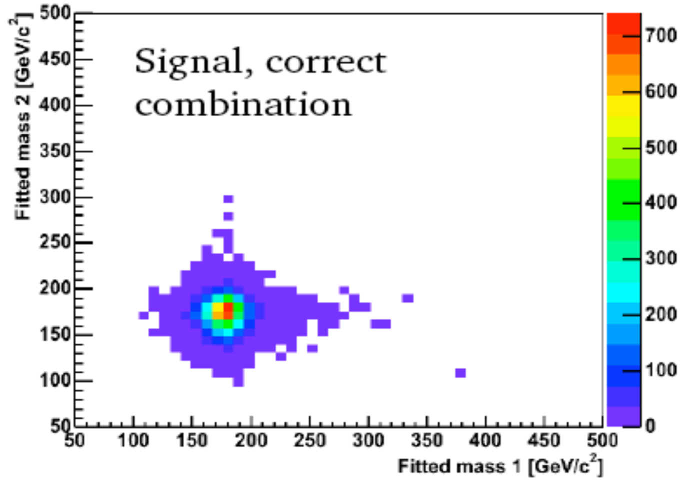



| Systematic $\Delta M_{top}$(GeV/c$^2$) | ME (CDF) | TMT (D0) |
|---|---|---|
| JES | 2.6 | 3.5 |
| Bkgd Shape | 0.8 | 0.2 |
| Sample composition | 0.7 | |
| ISR/FSR | 0.7 | 0.8 |
| Generators | 0.5 | |
| PDFs | 0.6 | 0.9 |
| MC stats | 0.8 | 0.3 |
| Method | 0.3 | 0.6 |
| **TOTAL** | **3.1** | **3.8** |

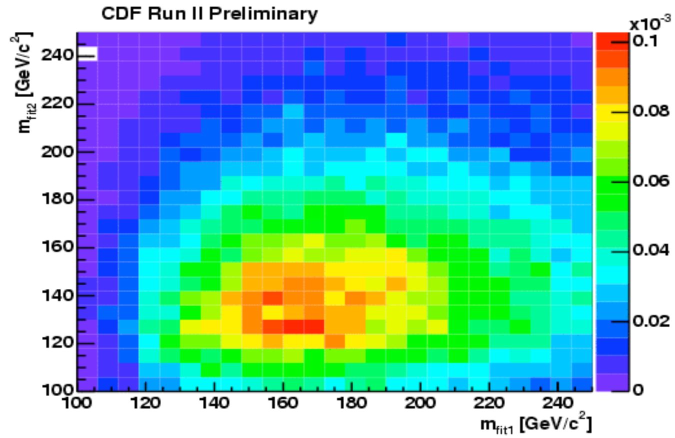
All consistent!!

# All-Jets

- Largest BR, and no missing information, but large backgrounds, S/B = 1: 8 even after 1 b-tag
- Event Selection
  - $E_T / \sqrt{(\Sigma E_T)} < 3\ (\text{GeV})^{1/2}$
  - $\Sigma E_T \geq 280$ GeV
  - $n_{b\text{-tag}} \geq 1$ (b-tag)
  - Exactly 6 jets




- $\chi^2$ kinematic Fitter with W mass contraint: fit two top quark masse s (m1, m2), then use $\chi^2$ value to weight each permutation




Bkgds (asymmetric)

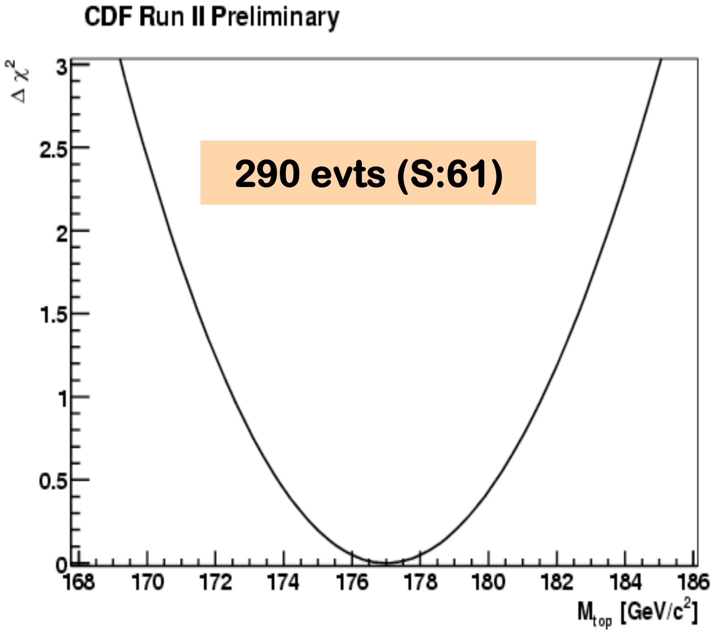
# Ideogram in All-jets

- 2D likelihood:

Convolution of Briet-Wigners and Gaussian resolution functions

$$L(M_{top}, C_s) = \sum_{i=1}^{90} w_i \left[ C_s Signal + (1 - C_s) Bkgd \right]$$

$$\text{where } Signal(m_i^1, m_i^2, \sigma_1^2, \sigma_2^2, M_{top}) = p_{mat} S_{mat} + (1 - p_{mat}) S_{comb}$$



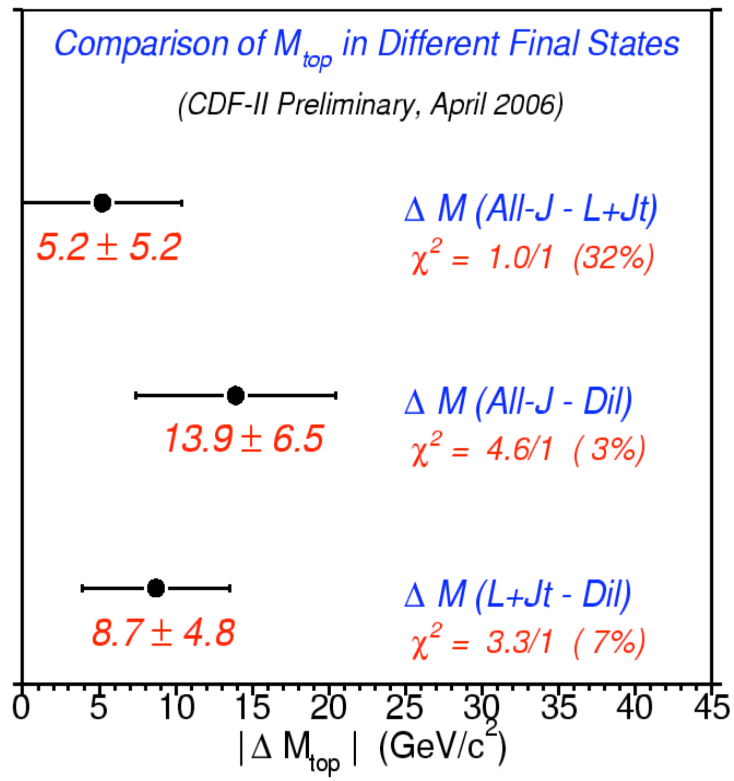

$$M_{top} = 177.1 \pm 4.9\,(stat) \pm 4.3\,(JES) \pm 1.9\,(syst)\; GeV/c^2$$

- First Tevatron Run II all jets $M_{top}$ measurement
- Systematically limited $M_{top}$ Results
- JES is correlated with S/B ratio

# Combining $M_{top}$ Results

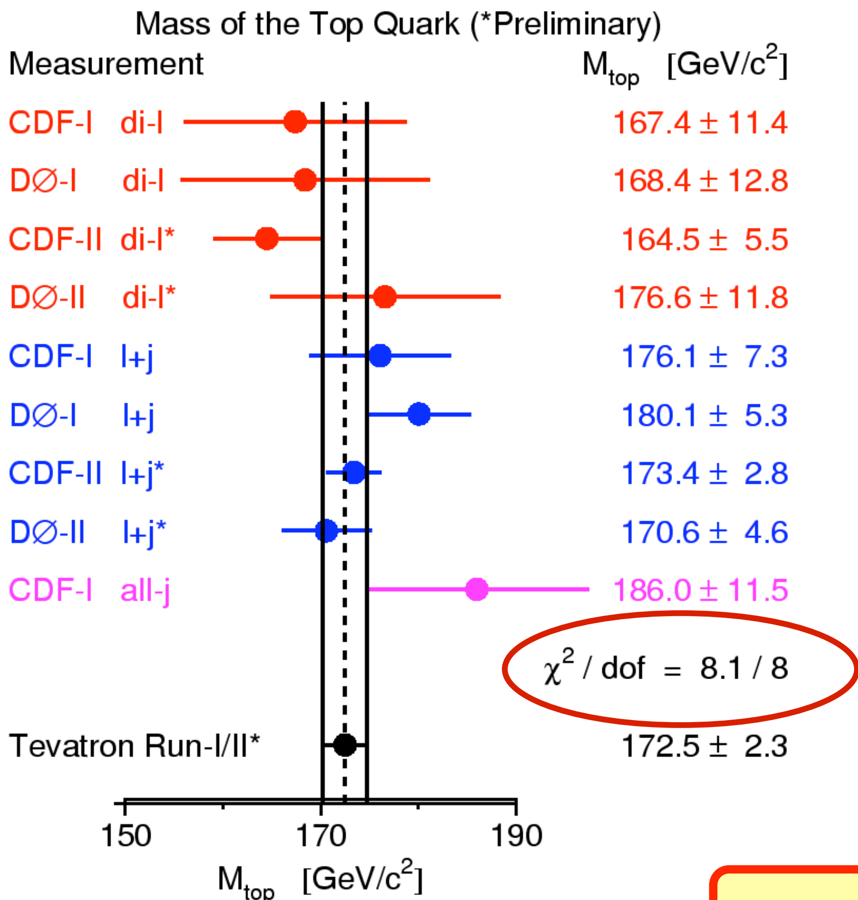
- Are the channels consistent ? (check by CDF)

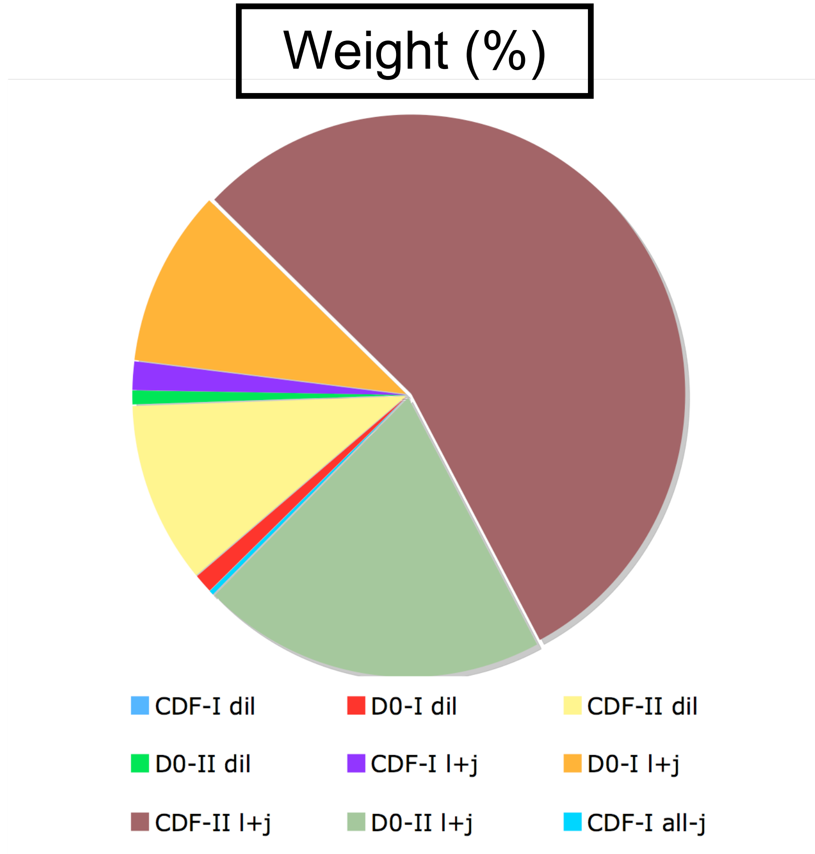
Mtop(All Jets) = 178.7 ± 5.5 GeV/$c^2$
Mtop(Dilepton) = 164.8 ± 4.8 GeV/$c^2$
Mtop(Lep+Jets) = 173.5 ± 2.8 GeV/$c^2$




- Any systematic shift?
  - Missing systematic?
  - Bias due to new physics signal?

# Tevaron Average




$$M_{top} = 172.5 \pm 2.3\ \mathrm{GeV}/c^2\ (1.3\%)$$

# Implication for Higgs and SUSY

- A Precision EWK Fit

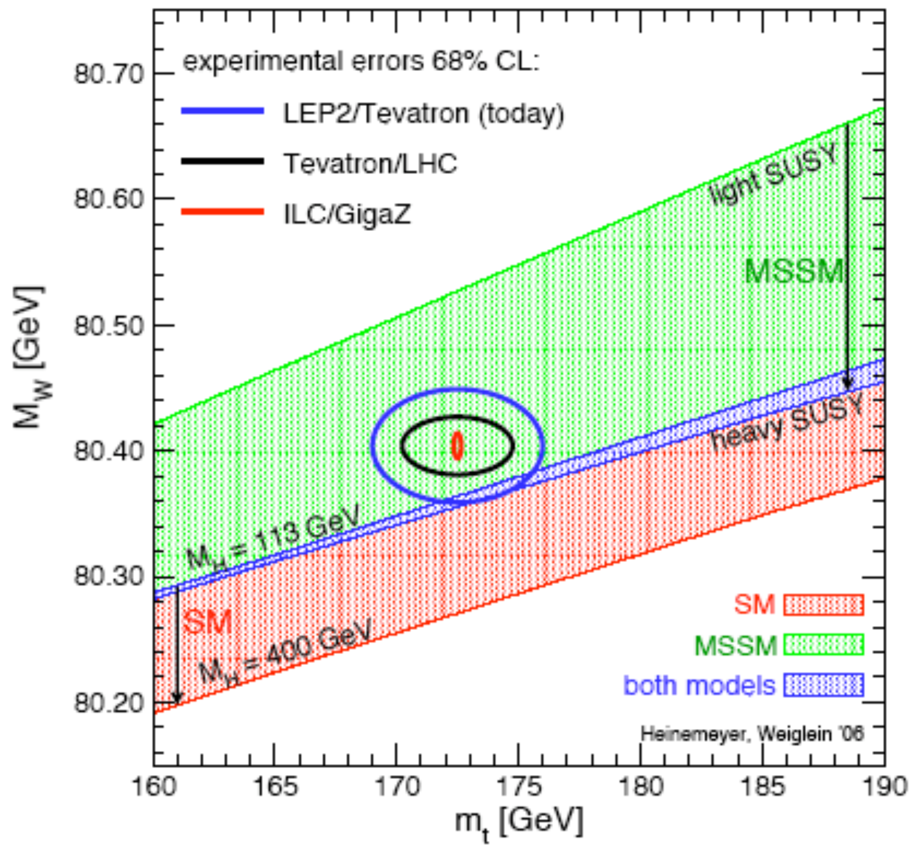
$$\boxed{M_H = 89^{+42}_{-30}\,\mathrm{GeV/c^2}}$$

$$\boxed{M_H < 175\,\mathrm{GeV/c^2}\ @95\%C.L.}$$

- Direct search(LEP):

  $M_H > 114$ GeV

- New result favors SUSY over SM, light SUSY



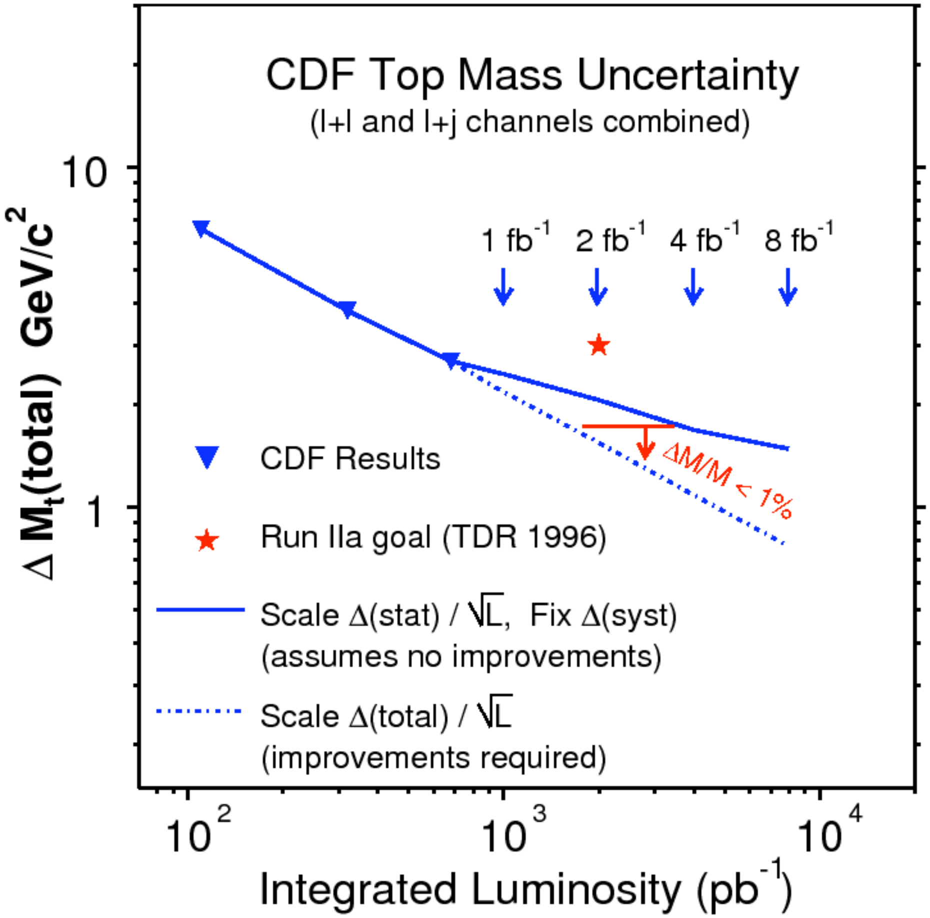

By Heinemeyer et al. (MSSM: $m_H$<140 GeV)

# Few Lessons from Tevatron

- A major JES uncertainty is greatly reduced by the Wjj in-situ calibration (40% improvement with 700pb-1 data)
- B-jet specific uncertainty is small (<0.7 GeV)
  - Heavy-quark fragmentation
  - Color-interference
  - Semi-leptonic decay
- Good b-tagger is important
- Effect of the higher order (NLO) is small at the Tevatron (<0.5 GeV)
- qq vs gg events have different kinematics
  (2-2.5 GeV difference in top mass: CDF)
- Effect of the multiple interaction is small
- Effect of the backgrounds is small (except all-jets channel)

# Summary and Future

- Achieved 1.3% precision of the Mtop measurement ( Run IIa goal, δMtop to ~ 3 GeV/$c^2$ using only 30% data )
- Developed many tools ( useful for LHC)
- With full Run-II dataset, able to achieve
  δMtop to < 1.5 GeV/$c^2$
- More precision
  and consistency!!!



# Syst. : ISR/FSR/NLO (backup)

- Method in hand to use Drell-Yan events to understand and constrain extra jets from ISR
  - Constraint scales with luminosity
  - Easily extendible to FSR.
- MC@NLO sample shows no add'l N LO uncertainty is needed.